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GEOMORPHOLOGY OF THE LAKE MALATA-LAKE GREENLY COMPLEX, SOUTH AUSTRALIA, AND ITS IMPLICATIONS FOR LATE QUATERNARY PALAEOCLIMATE

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Summary

DUTKIEWICZ, A., VON DER BORCH, C. C. AND PRESCOTT, J. R., (2002). Geomorphology of the Lake Malata-Lake Greenly complex, South Australia, and its implications for late Quaternary palaeoclimate. *Trans. R. Soc. S. Aust.* **126**(2), 103-115, 29 November, 2002.

Lunettes, foredunes and beach ridges from the Lake Malata-Lake Greenly playa complex on the Eyre Peninsula attest to major changes in lake level and palaeoclimate over the last 320,000 years. These have been dated by a combination of thermoluminescence and radiocarbon techniques, thus allowing correlation with Late Quaternary Oxygen Isotope stages. The lakes experienced a major wet phase ca. 320 ka followed by multiple arid episodes linked to relatively cool periods and low eustatic sea-levels between 115-16 ka. Aeolian activity and aridity were particularly intense during the Last Glacial Maximum with the onset of a dry climate and carbonate pellet lunette-building commencing as early as 26 ka. The Holocene palaeoclimate is marked by seasonally oscillating wet and dry periods reflected in the intermittent deposition of gypsum lunettes, carbonate ridges and quartz foredunes around the eastern margins of lakes Malata and Greenly.

KEY WORDS: Quaternary palaeoclimate, salt lakes, Lake Malata, Lake Greenly, lunettes, thermoluminescence dating, Bridgewater Formation, carbonate, gypsum.

Introduction

Lake basins are one of the richest archives of terrestrial palaeoclimate data (e.g., Williams *et al.* 1998; Mason *et al.* 1994; Rodó *et al.* 2002). In particular, surficially-closed basins such as salt lakes are extremely sensitive to changes in climate and respond accordingly by adjusting their lake and groundwater levels. They are widespread in south-western, south-eastern and northern parts of Australia where they often represent the termini of large endoreic basins (e.g., Bowler & Magee 1988; Magee *et al.* 1995; Macumber 1991; Bowler 1971). As salt lakes are susceptible to drying and erosion, one of the most challenging aspects associated with their study is resolving the problem of discontinuous stratigraphic records. This, however, can be achieved by examining and dating not only the sedimentary succession in the basin itself, but also the geomorphologic features such as beach ridges and lunettes, as these invariably formed during major changes in lake levels and climate. In this study we describe strandline features of the Lake Malata-Lake Greenly Complex (Fig. 1), which contain a rich record of major climate change exposed along its eastern shores. Most of these features have been dated by thermoluminescence and radiocarbon dating and provide a framework for late Quaternary climate change in South Australia. These are discussed in detail in this paper.

Fig. 1. Map of Eyre Peninsula showing the location of the Lake Malata-Lake Greenly Complex.

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General Setting

The Lake Malata-Lake Greenly Complex consists of a chain of north north-east trending Quaternary carbonate-evaporite playa lakes, situated approximately 33 m above mean sea level in a mid-latitude region on lower Eyre Peninsula, South Australia (Fig. 1). The main basins, Lake Malata and Lake Greenly, are separated by an extensive easterly trending calcareous, sub-parabolic dune system, which forms the main regional aquifer. Emplacement of these dunes during the late Quaternary sea-level highstands (Wilson 1991)[1] most likely caused the damming of a pre-Pleistocene drainage channel, with subsequent groundwater seepage along the dune lobes facilitating formation of lakes Malata and Greenly. Both basins are eroded along their south-west margins with adjacent basement rocks up to 5 metres above the present-day lake floor suggesting a graben-type depression. Numerous smaller playas, located exclusively to the east of the main basins, appear to have formed much later, via the interactive processes of deflation and groundwater discharge. Hydrologic, stratigraphic and geomorphologic evidence collected to date indicates that the main basins have never been surficially connected.

At present, all lakes in the Lake Malata-Lake Greenly Complex are ephemeral groundwater-discharge playas characterised by a cm-thick halite crust during the dry summer months. Depths of up to 0.5 m of water, partly due to direct precipitation and partly due to reduced evaporation exist during the wet winter months. The solutes are derived from marine salt accession via aerosols and by evaporation of inflow (surface and groundwater), which delivers chemical weathering products from surrounding sedimentary and basement rocks and syndepositional recycling of evaporites. The hydrology and geochemistry of the main basins have been discussed elsewhere (Dutkiewicz *et al.* 2000). Although defined by the same mineralogical suite, basin sediments from Lake Greenly and Lake Malata are distinctly different. Lake Greenly sediments are dominated by carbonate mud (calcite and dolomite) measuring several metres to decimetres in thickness, with the uppermost 3 m of the basin sequence interbedded with dm-thick layers of gypsarenite (Dutkiewicz & von der Borch 1995). In contrast, Lake Malata is dominated by gypsum, which occurs in the form of relatively mud-free, m-thick gypsarenites, and mm-thick gypsum-clay laminae which overlie a cemented skeletal peloidal grainstone near the base of the succession. The skeletal peloidal grainstone overlies weathered basement. The difference in the relative abundance of carbonate and gypsum over the lake complex is related to the local hydrologic setting of each basin and rainfall/recharge distribution over the region.

Geomorphology

The morphology of the playa lakes depends on the nature of the pre-existing surface, the angle of the long basin axis to the direction of the prevailing wind, the presence and depth of surface water, the proximity of the groundwater to the lake surface and playa-groundwater chemistry. Aeolian reworking, ground and surface water fluctuations and interactions play a secondary role in modifying the lake geomorphology, which ultimately reflects major changes in climate. A number of geomorphologic features directly associated with the Lake Malata-Lake Greenly Complex include islands, spits, lunettes, irregular sub-parabolic dunes, beach ridges, sandy beaches, marginal seepage-spring zones and surface drainage channels (Fig. 2). In this

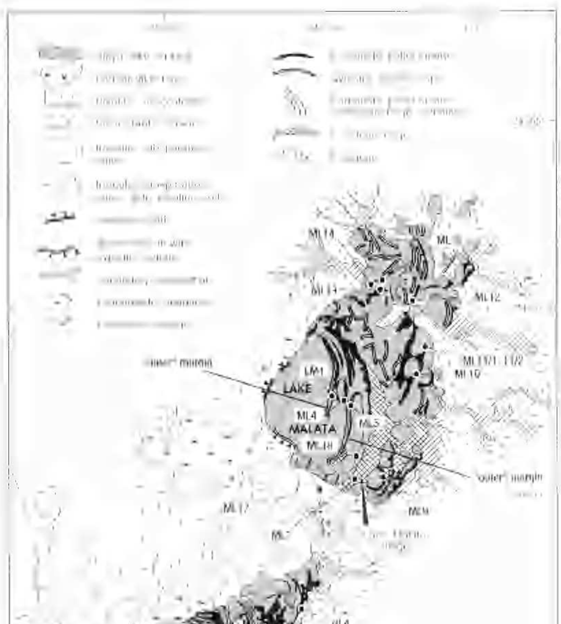

Fig. 2. Geomorphologic map of the Lake Malata-Lake Greenly Complex showing the location of TL and AMS dated samples.

[1] Wilson, C.C. (1991). "Geology of the Quaternary Bridgewater Formation of the Southwest and Central South Australia" PhD thesis, The Flinders University of South Australia (Unpubl.).

Table 1. Thermoluminescence and ^{14}C ages of key geomorphologic features.

Sample Name	Geomorphologic Feature	Description	Dating Method	Age
LM1	Gypsum lunette/Gypsum dune	Coarse-grained, moderately-sorted gypsarenite overlain by a gypsite capping.	AMS	4.81 ± 0.09 ka B.P.[*] 5.59 (2s = 5.32-5.72) ka cal B.P.[**]
ML4	Carbonate pellet lunette	Slightly pelletal, clayey carbonate overlain by an indurated carbonate layer.	TL	16.1 ± 1.2 ka
ML5	Carbonate pellet lunette	Slightly gypsiferous and pelletal clayey carbonate overlain by an indurated carbonate layer.	TL	53.9 ± 4.4 ka
ML7	Foredune ridge (Lake Malata ridge)	Strongly cemented, well-sorted, medium to coarse-grained skeletal peloidal grainstone.	TL	319 ± 52 ka[+]
ML9	Carbonate pellet lunette	Gypsiferous, slightly clayey, pelletal carbonate.	TL	115 ± 14 ka
ML10	Carbonate pellet lunette	Slightly pelletal carbonate overlying an indurated nodular carbonate layer. Abundant iron-stained quartz.	TL	84.5 ± 9.3 ka
ML11/1	Carbonate pellet lunette	Clayey carbonate overlain by an indurated carbonate layer.	TL	43.4 ± 3 ka
ML11/2	Carbonate pellet lunette	Pelletal carbonate overlying an indurated carbonate layer.	TL	15.6 ± 0.7 ka
ML12	Carbonate pellet lunette	Slightly gypsiferous pelletal carbonate overlying a moderately indurated chalky carbonate layer.	TL	17.5 ± 1.1 ka
ML13	Carbonate pellet lunette	Strongly indurated nodular carbonate layer.	TL	75.1 ± 5.4 ka
ML14	Carbonate pellet lunette	Pelletal carbonate mud overlying Coxiella sand.	TL	1.17 ± 0.1 ka
ML15	Carbonate pellet lunette	Pelletal carbonate mud overlain by cobbles of weakly to moderately indurated chalky carbonate.	TL	17.3 ± 0.8 ka
ML17	Sub-parabolic dune	Moderately cemented, well-sorted, medium-grained skeletal peloidal grainstone.	TL	70.6 ± 3.2 ka
ML18	Quartz foredune	Moderately-sorted, medium to coarse-grained quartz sand. Abundant Coxiella, ostracode and foraminifer fragments.	TL	1 ± 0.09 ka 0.26 ± 1.93 ka[‡]
GL4	Carbonate pellet lunette	Pelletal carbonate overlain by cobbles of weakly to moderately indurated chalky carbonate.	TL	26 ± 1.7 ka
GL8	Carbonate pellet lunette	Slightly pelletal and clayey carbonate mud.	TL	96.3 ± 13.9 ka

[*] dated by accelerator mass spectrometry (AMS): Lab No. OZB152U; conventional (uncalibrated) age
[**] calibration based on Stuiver and Reimer (1993) and Stuiver et al. (1998)
[+] average of two ages (312 ± 67 ka and 325 ± 77 ka: Dutkiewicz & Prescott 1997)
[‡] the younger age indicates remobilisation of the foredune obtained using the double plateau on the plateau test (Dutkiewicz & Prescott 1997)

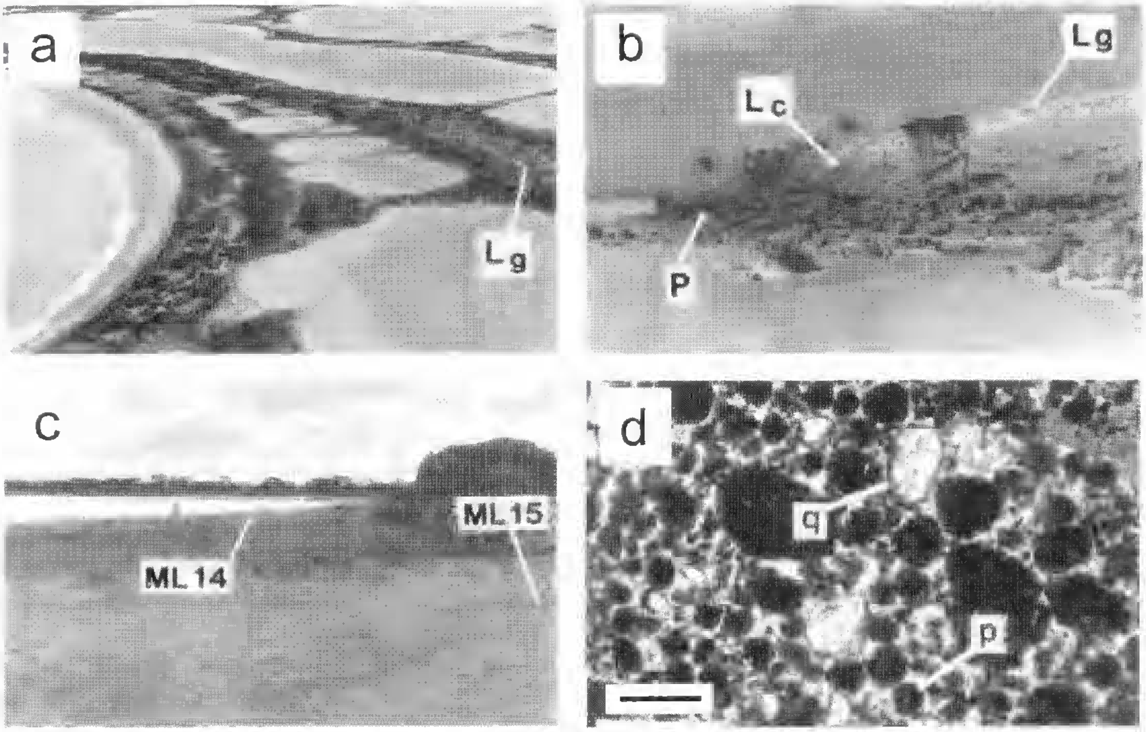

Fig. 3. (a) A chain of playa lakes that have previously deflated into a gypsum lunette (L_g). View is towards the north. Centre of photograph spans approximately 600 m. (b) A 5 to 6 m-high, truncated lunette profile at the south western margin of Lake Greenly. Basement is unconformably overlain by an indurated pedogenic horizon (P), which is in turn overlain by an altered carbonate pellet lunette (L_c). Gypsite layer (L_g) overlies L_c with a gradational contact. (c) Lee side of two carbonate pellet lunettes (~1.17 ka ML14 and ~17.3 ka ML15) along the eastern margin of a small playa lake north of Lake Malata, forming a prograding lunette sequence separated by a samphire-vegetated mud flat. These represent Phase III and Phase I deposition events in Fig. 4. (d) Thin-section photomicrograph showing bimodal carbonate pellets (p) with a minor amount of well-rounded carbonate-coated quartz (q) of similar grain-size. Plain light. Scale is 0.25 mm.

paper we describe some of the key geomorphological features ranging in age from 319 ± 72 ka to 1 ± 0.9 ka (Dutkiewicz & Prescott 1997; Fig. 2, Table 1) which formed as a result of major climate change.

Lunettes

Although clay, quartz and gypsum are the most common minerals comprising lunettes (crescentic dunes associated exclusively with playa lakes; e.g., Bowler 1983; Warren 1982; Williams *et al.* 1991; Chen *et al.* 1991; Macumber 1991), those in the Lake Malata-Lake Greenly Complex consist either of gypsum sand or sand-sized carbonate pellets. In general, the gypsum and carbonate pellet lunettes are part of a prograding sequence, which rises 2 to 3 m above the present-day lake floor. They are characterised by at least two disconformities in the form of pedogenic layers or erosional scarps and younger deflation basins (Figs 3a, b, c). The lunettes occur along the eastern margins of most playas in the complex and provide a partial indication of the amount of material that has been deflated from the lake basins. Their associated pedogenic horizons (disconformities) are potential time-stratigraphic markers for strandline-basin correlations.

Four discrete units representing four major phases of lunette deposition have been recognised from exposed sections and dated by TL between 115 ± 14 ka and 1.17 ± 1.1 ka (Dutkiewicz & Prescott 1997; Fig. 4). The distinction is based largely on the degree and style of pedogenic alteration of the indurated carbonate layer (disconformity) overlying the soft lunette material, and field relationships of lunette deposits. Notably, progressive pedogenesis and loss of original pelletal texture are a function of increasing age while the composition and colour of the lunettes and pedogenic horizons reflect the immediate source area. Internal structures, such as low-angle planar beds normally expected from seasonal accumulation, are very diffuse or non-existent and are attributed to the breakdown of pellets by moisture and pedogenesis. Individual deposits may reflect multiple phases of lunette deposition and stabilisation, although the general

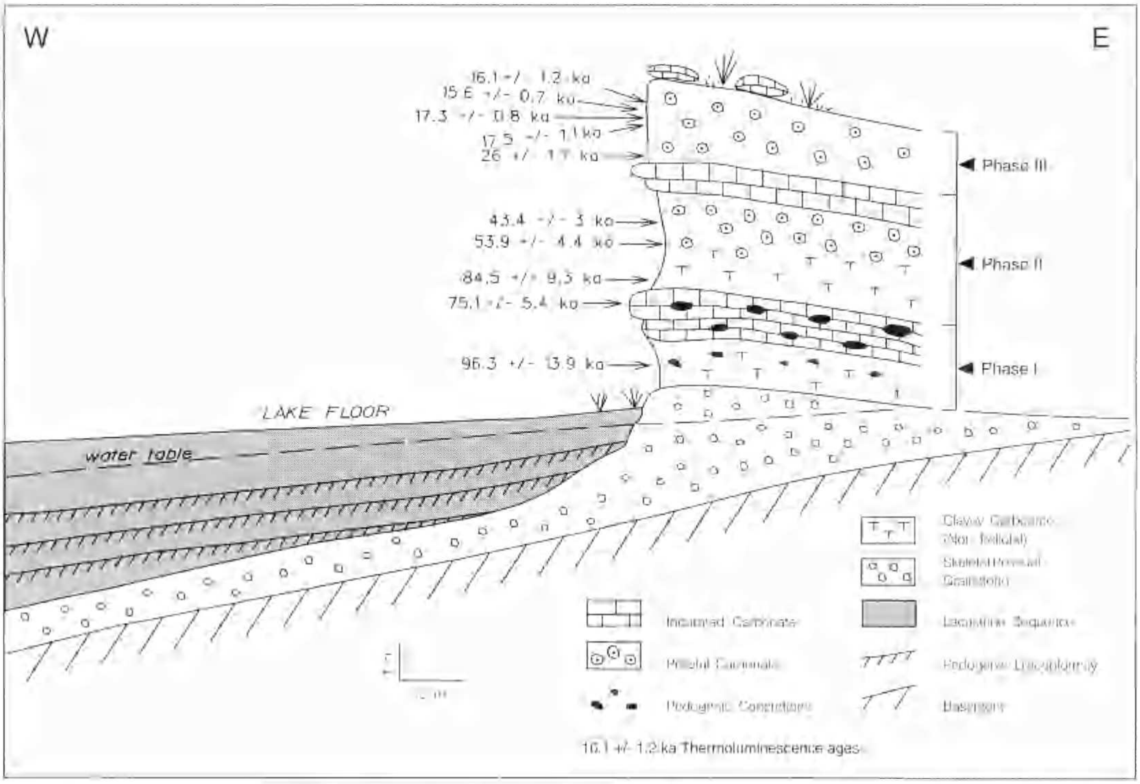

Fig. 4. Idealised schematic west-east section of Lake Malata showing three major phases of carbonate pellet lunette deposition in a single onlapping sequence. Thermoluminescence dates are also shown.

homogeneity of the deposits makes differentiation of these difficult.

The pelletal fraction consists almost exclusively of low-Mg calcite and minor clay minerals dominated by montmorillonite. The coarse, non-pelletal fraction usually contains minor amounts of abraded gypsum discoids or prisms, quartz, iron oxides, peloids, foraminifera, ostracode carapaces and *Coxiella* fragments, and trace amounts of lithoclasts, pyrite and remnants of algal mats including rare charophyte oogonia. In thin-section and under the scanning electron microscope (SEM), the carbonate lunettes consist of bimodal sand-sized carbonate pellets and minor sand-sized quartz (Fig. 3d). Quartz grains tend to be well-rounded and carbonate-coated, while gypsum is discoidal, poorly-sorted, shows effects of dissolution and abrasion and frequently occurs as semi-cemented aggregates. Gypsite nodules are common in the gypsiferous lunettes.

In general, the degree of pedogenic alteration corresponds with the age of the lunette and conforms with Netterberg's (1967) calcrete classification. For example, the oldest lunettes show intense pedal development in the form of cavernous, nodular calcrete and complete loss of the original pelletal structure in the underlying deposit. Younger lunettes, on the other hand, are capped by a chalky, powdery calcrete or more massive and strongly indurated hardpan calcrete, both of which are nodule-free and frequently comprise several undulose sheet layers which themselves reflect multiple phases of pedogenesis. These are overlain either by thin veneers of pelletal soil or younger, onlapping lunette deposits. The youngest lunettes display a strong pelletal fabric with samphire vegetation acting as the main post-depositional stabiliser.

Three major phases of gypsum lunette formation have been identified in this study. The best examples occur virtually along the entire lengths of the inner and outer margins of eastern Lake Malata (Fig. 2) where the lunettes form a prograding, cross-bedded sequence measuring up to 7 m above the present-day lake (Fig. 5a). An organic-rich layer within the core of the main lunette has been dated by AMS at 5.59 ka cal B.P. and is currently being mined for gypsum for agricultural purposes. The cliffed sections of the Lake Malata lunettes are onlapped by clean, well-sorted gypsarenite which forms the present-day beach. The lunette sequences are stabilised by a weakly indurated 40 cm to 3 m-thick capping of gypsite which is colonised by abundant salt-tolerant shrubs and samphire vegetation. The relationship

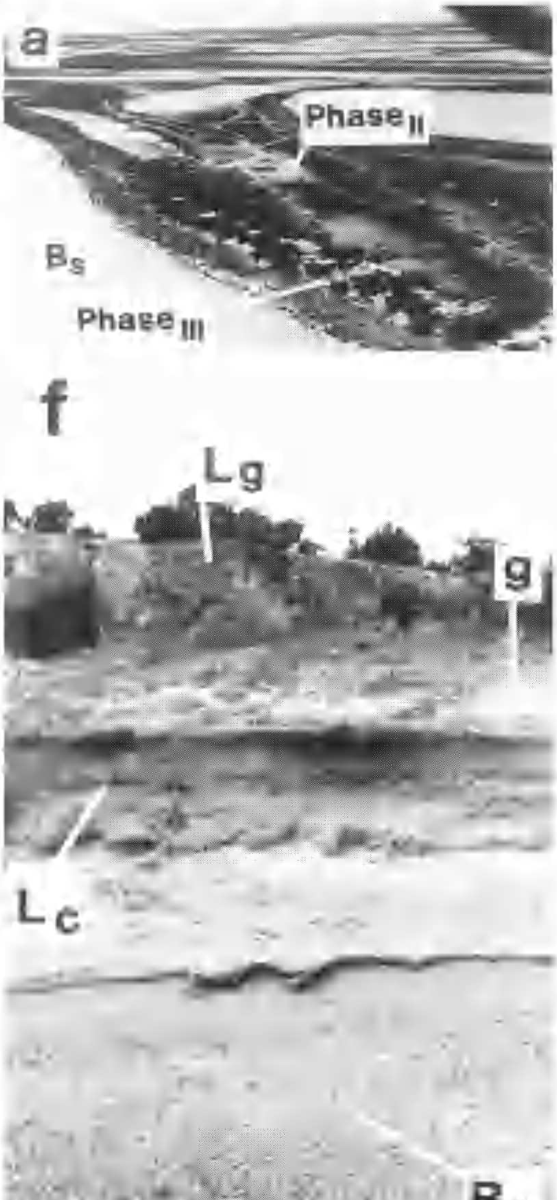

Fig. 5. (a) Two phases of gypsum lunette deposition along the inner eastern margin of Lake Malata. Beach sand (B_s) consists of coarse-grained gypsarenite. Younger Phase III gypsum lunettes are stabilised entirely by vegetation. Distance from the Lake Malata margin to playa lake immediately behind Phase III lunette is 400 m. (b) Gypsum lunette (L_g) representing Phase II gypsum lunette deposition overlying a clayey carbonate pellet lunette (L_c) along the outer eastern margin of Lake Malata. Poorly-sorted, coarse-grained beach sand (B_s) comprising basement and skeletal peloidal grainstone lithoclasts forms the present-day beach. Note presence of coarse-grained white gypsum sand (g) onlapping L_c.

between the gypsum and carbonate lunettes is not always clear, as the gypsum lunettes are generally larger and more extensive, completely obscuring underlying units which essentially become barriers for their development. Along the outer south-eastern margin of Lake Malata and the south-western margin of Lake Greenly, exposed sections clearly show a gypsum lunette overlying a carbonate pellet unit (Fig. 5b). However, farther north and along the inner margin of Lake Malata, the gypsum lunettes appear to extend in a southerly direction away from the flanks of the carbonate lunettes without directly overlying the carbonate pellet units in exposed sections. Field relationships and a single AMS date suggest that the gypsum lunettes are generally younger than the carbonate pellet lunettes.

The gypsum lunettes consist almost entirely of medium to coarse-grained, moderately to well sorted gypsarenite with small amounts of carbonate (low-Mg calcite) and trace amounts of fine-grained quartz and iron oxides. Consequently, the gypsum lunettes were unsuitable for TL dating and only in one case contained sufficient organic carbon for ^{14}C dating. The carbonate content may be attributed either to the presence of carbonate pellets, carbonate coating the gypsum crystals during their growth in the lake basin, or to biogenic components. Fragments of ostracodes, *Coxiella* and the foraminifer *Elphidium* are common within the uppermost 65 cm of the most recent gypsum lunettes. The gypsarenite consists of 1-4 mm long, slightly abraded anhedral lensoids, marked by dissolution kinks. The thickness of the gypsite capping varies between 40 cm to 3 m and is a function of the size and the age of the lunette. The thicker and the more indurated the gypsite horizon, the older the lunette. The gypsite consists entirely of 10 μm long acicular crystals under the SEM. Gypsite also occurs as cm-thick interbeds within the gypsum lunette where it most likely represents stabilisation of individual, possibly annual, aeolian layers. In the same manner that the indurated carbonate layers represent disconformities within the carbonate pellet lunettes sequence, the gypsite units represent periods of non-deposition within the gypsum lunettes. Low angle aeolian bedding is well-developed within the gypsum lunettes and reflects grain-size variations and general sorting of the gypsarenite within the individual laminae.

Beach Ridges and Foredunes

The most distinct geomorphologic feature associated with the Lake Malata-Lake Greenly Complex is a 9 m-high, arcuate, indurated skeletal peloidal grainstone beach ridge dated by TL at 319 ± 52 ka (Dutkiewicz & Prescott 1997: Table 1), which is present along the eastern margin of Lake Malata ("Lake Malata Ridge" in Figs 2 and 6). The ridge has

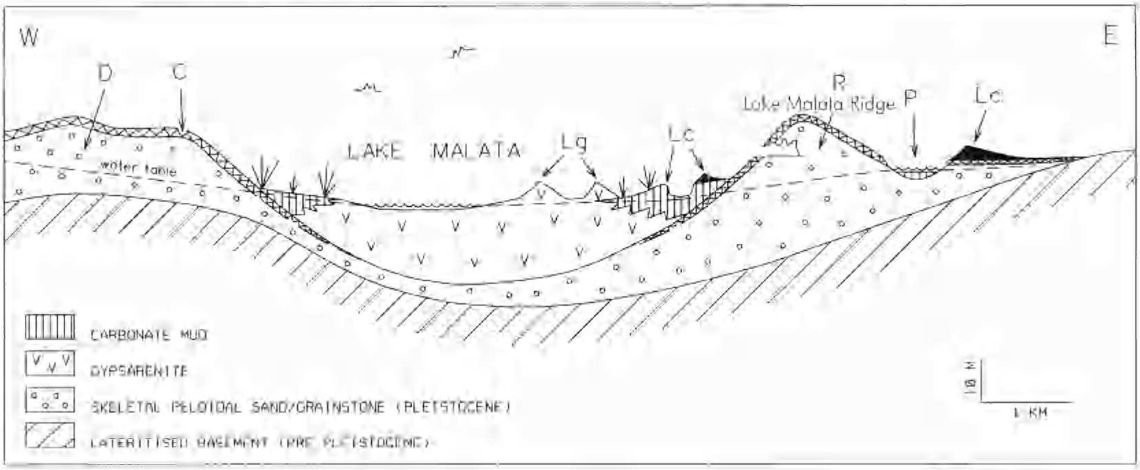

Fig. 6. Schematic west-east section across Lake Malata showing the western margin of the lake basin bordered by calcretised (C) sub-parabolic dunes (D), and the eastern margin by a major arcuate ridge (R) and a series of transverse gypsum lunettes (L_g) and carbonate pellet lunettes (L_c), and small playa lakes (P).

been correlated with a similar grainstone sampled by drilling, which overlies the basement in the Lake Malata basin (Dutkiewicz 1996)[2] and represents the largest and quite possibly the oldest geomorphologic feature associated with the lake complex. The ridge is cavernous and has an up to 10 cm-thick capping of calcrete, which is locally overlain by a thin red soil containing abundant ferruginous pisolites. The ridge sediments outcrop sporadically along the south-western margin of Lake Malata where they are overlain unconformably by a gypsum lunette. Sedimentary structures were not observed, possibly due to calcretisation and a general lack of outcrop and exposure. The beach ridge consists of a locally tufaceous, medium-grained, well-sorted skeletal peloidal grainstone comprising sub-rounded to well-rounded micritised peloids, abundant mollusk fragments, coralline red algae, foraminifera, minor echinoid fragments, rare bryozoa and varying amounts of lithoclasts and angular quartz grains (Fig. 7a). Its composition correlates well with the Bridgewater Formation, which comprises surrounding sub-parabolic dunes and spectacular cliffs on the west coast of the Eyre Peninsula (Wilson 1991)[1].

More recent but pervasive beach deposits are found around the shorelines of Lake Malata and Lake Greenly and associated playa lakes. The composition of the beach sand depends largely on the source and its thickness on the sediment supply and the proximity of the source to the lake margin, the water depth, and the fetch of the lake. For example, poorly-sorted, very coarse sands and gravels are associated with basement outcrops. Thick (up to 3.5 m), localised accumulations of beach sand are common along the south-western margin of Lake Greenly and southern Lake Malata, where they consist of very coarse angular quartz, lithoclasts of basement rock, calcrete, and skeletal peloidal grainstone, iron oxides, feldspar, mica, and skeletal peloidal allochems derived from surrounding sub-parabolic dunes. Fragments of *Coxiella* sp., ostracodes, foraminifera and charophyte oogonia are occasionally incorporated. Medium to coarse-grained, moderately-sorted, skeletal peloidal sand, on the other hand, forms a beach along the southern margin of Lake Greenly where the source is a set of parabolic dunes proximal to the lake basin. In contrast, carbonate playa lakes associated with Lake Greenly are characterised by shorelines dominated by biogenic fragments including ostracode valves, *Coxiella* sp., foraminifera and minor charophyte oogonia. These are occasionally very weakly indurated. Beaches associated with Lake Malata, on the other hand, are dominated by coarse-grained gypsarenite and fragments of *Coxiella* sp.

A 3 m-high foredune along at the south-eastern margin of Lake Malata situated less than 200 m west of the Lake Malata ridge is of particular interest (Fig. 7b) and has a maximum TL age of 1 ± 0.09 ka (Dutkiewicz & Prescott 1997; Table 1). It also hosts an undisturbed Aboriginal campsite comprising a stone grinding plate and scraping tools. The beach consists of medium to coarse-grained, moderately-sorted sand dominated by coarse to fine-grained, angular to well-rounded quartz, moderate amounts of

[2] Dutkiewicz, A. (1996) "Quaternary Palaeoclimate from Lake Malata-Lake Greenly Playa Complex, South Australia" PhD thesis. The Flinders University of South Australia (Unpubl.)

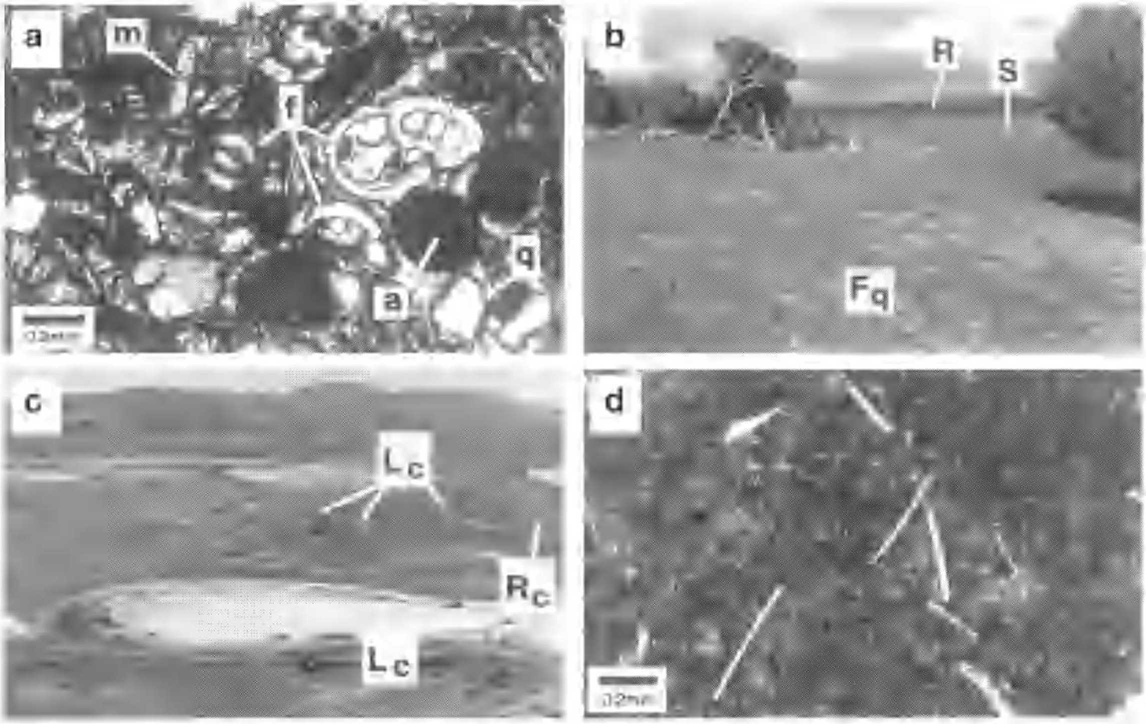

Fig. 7. (a) Thin-section photomicrographs of the skeletal peloidal grainstone comprising the Lake Malata Pleistocene ridge. The grainstone is composed of abundant foraminiferal (f), molluscan (m), calcareous red algal (a) and peloidal allochems. Quartz (q) is also present. The grainstone is strongly cemented by micrite. Polarised light. (b) 3 m-high quartz foredune (F_q) separated from the Lake Malata ridge (R) by an ephemeral seepage-spring zone (S) measuring approximately 150 m in width. The foredune has a maximum TL age of ~1 ka. Trees are approximately 2 m tall. (c) Aerial view of the eastern margin of Lake Greenly characterised by a prograding sequence of low-lying carbonate pellet lunettes (L_c) and carbonate ridges (R_c). Centre of photograph spans 750 m. (d) Thin section photomicrograph of sediment comprising R_c in (c) composed of abundant ostracode fragments within a micrite matrix. Plain light.

medium-grained peloids, and fragments of *Coxiella* sp., ostracodes and foraminifera. Carbonate pellets with approximately 40% fine to medium-grained quartz sand are present at a depth of 1 m below the surface. Farther south, the deposit grades into very coarse-grained and poorly-sorted beach sand approximately 1 m above the present-day lake floor. The sand is dominated by fine to coarse-grained, angular and occasionally iron-stained quartz and fragments of *Coxiella* sp. Moderate amounts of lithoclasts derived from skeletal peloidal grainstones and calcretes, minor amounts of peloids and feldspar, and trace amounts of charophyte oogonia and mica, are also present. Here, the sand overlies a dm-thick humic coquina layer dominated by fragments of *Coxiella* sp., minor amounts of quartz, and trace amounts of foraminifera, ostracodes, charophyte oogonia, peloids, mica and recent vegetation. This layer, in turn, overlies a strongly indurated skeletal peloidal grainstone which outcrops thinly along the margin of the lake.

The geomorphologic features along the eastern margin of Lake Greenly are strikingly different from those of Lake Malata. This is attributed mainly to the differences in basin morphologies, particularly the orientation of the long basin axis to the direction of the prevailing wind, the nature of the basin sediments, and the groundwater chemistry. The associated lunette-ridge system is low in relief and difficult to map but unmistakable when seen from air (Fig. 7c). In fact, mapping of the individual lunettes and ridges could only be achieved using aerial photography. In addition, exposed lunette sections are rare and lunettes appear to have formed a prograding sequence, sourced by episodic deflation within Lake Greenly. Unlike the prograding lunette sequence at Lake Malata, where individual lunettes are separated by deflationary basins, the Lake Greenly lunettes appear to be separated by a series of carbonate ridges. The ridges are very similar in hand specimen and in outcrop style to the indurated carbonate horizons associated with lunettes, which makes the distinction of these features extremely difficult in the field.

The most easily recognised carbonate ridges occur proximal to the present-day northeastern lake margin, where four ridges representing four phases of lake regression have been recognised. The ridges are approximately 2 to 3 m above the present-day floor of Lake Greenly and form fractured and rubbly carbonate sheets. They lack the smooth and continuous arcuate outcrop style common to indurated carbonate horizons associated with lunettes. The crusts consist of low-Mg calcite and are chalky and friable, with a mm-thick coating of laminar calcrete. Tubular voids are abundant more so than in the indurated carbonate horizons associated with carbonate pellet lunettes and appear to be related to plant growth in relatively soft sediment. However, no fossil plant remains were found. Scanning electron microscope analysis of these crusts shows the presence of abundant, straight or gently curved, occasionally branching, ~ 5 μm-thick calcite-encrusted endolithic fragments. The morphology and size of these filaments are consistent with fungal structures described by Klappa (1979) and indicate pedogenesis in the subaerial vadose environment. In thin-section, the crusts consist of micrite, which occasionally displays a globular texture and abundant, generally randomly oriented, calcitic shell fragments which comprise 5 to 15% of the total sediment (Fig. 7d). The shell fragments consist of low-Mg calcite and are generally straight or gently curved, approximately 10 μm in diameter and generally 1 to 2 mm in length and most likely represent disarticulated ostracode valves. Foraminiferal fragments are rare. The deposits have not been dated due to the paucity of suitable materials such as organic matter and quartz.

Discussion

The Late Quaternary geomorphology in the Lake Malata-Lake Greenly Complex is represented by a complex suite of ridges, lunettes and foredunes which have been dated between 320 ka and 1 ka. The period covers a time of dramatic climatic oscillations during which the formation of the lake complex was initiated and the lakes experienced a major lacustral (wet) phase followed by a series of drying and deflationary episodes punctuated by periods of pedogenesis and relatively minor lacustral events. Oscillations between these climatic extremes culminated in the present-day status of the lakes as groundwater-discharge playas.

Wet phase ca. 320 ka

The main lacustral phase is represented by the *ca.* 320 ka (Oxygen Isotope Stage 9; Fig. 8) Lake Malata beach ridge (Figs 2 and 6) deposited during a phase of high lake level. Its morphology is consistent with foredune deposition and we envisage that it formed by deflation of sand from wave-nourished lakeshore beaches in very much the same manner that coastal foredunes and foredune ridges are built immediately behind zones of beach swash. Prior to stabilisation of the surrounding sub-parabolic dunes, a large amount of the skeletal peloidal sand was blown and washed into the lake basin and subsequently reworked by wind-generated waves during a pluvial climatic phase. A combination of relatively lower than present evaporation rates, highly effective precipitation, increased runoff and recharge and high water tables, associated with an interglacial sea-level highstand, would have resulted in the accumulation of relatively fresh water within the lake basin. The size of the ridge suggests that at least 1 m of water was present in the lake basin during the wet winter months, which would have been characterised by higher rainfall and lower evaporation relative to present. Such a relatively high lake level, combined with strong north-westerly winds associated with the winter months, would have initiated wave-generated currents capable of moving large volumes of the skeletal peloidal sand as bedload towards the eastern, and particularly the south-eastern lake margin where the ridge attains its maximum width. Under these conditions the sand accreted on the eastern lakeshore of Lake Malata as a beach deposit and was subsequently deflated by strong south-westerly winds into a foredune immediately behind this high-energy beach. The height of the beach ridge attests to the fact that this period was relatively long-lived, characterised by enhanced seasonality and a large and continuous sediment supply. The ridge was eventually stabilised by pedogenesis and vegetation during an extended period of non-deposition. That only one such feature is present within the Lake Malata-Lake Greenly Complex indicates a unique depositional episode. The absence of a similar foredune ridge along the eastern margin of Lake Greenly may be attributed not only to a lack of sediment supply, but also to the basin morphology, particularly the orientation of the long axis to the direction of the prevailing westerly wind. The Lake Greenly basin is oriented approximately at 45° to the direction of the prevailing westerly wind, while the Lake Malata axis lies at 90°.

Consequently, the ridge represents a Pleistocene "megalake" or "lacustral" stage (*sensu* Bowler 1980, 1981; De Deckker 1988) in the evolution of the lake basin and overlaps with Wilson's (1991) Phase III deposition of Bridgewater Formation dunes during mid to late Pleistocene interglacial sea-level highstands. Megalake shorelines, such as a 13.5 m-high beach at Lake Tyrrell, contain abundant shells of *Coxiella* sp. (Macumber 1980; Bowler &

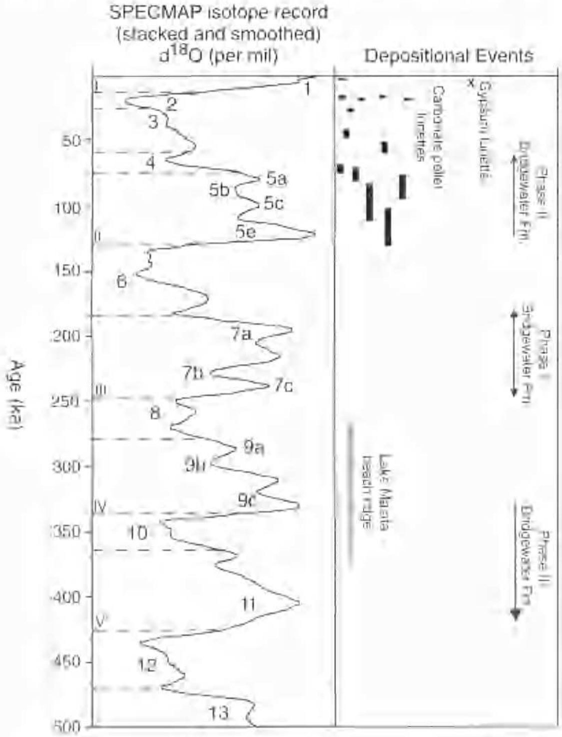

Fig. 8. Ages of major geomorphologic features in the Lake Greenly-Lake Malata complex plotted against the SPECMAP curve (Imbrie *et al.* 1989; McIntyre *et al.* 1989). Ages of the isotope stages 1 to 6 after Martinson et al. (1987). Ages for the deposition of the Bridgewater Formation after Wilson (1991). Roman numerals denote glacial terminations. The length of each bar indicates uncertainty in measurement of the age of lunette/ridge (see Table 1 for detail).

Teller 1986). Curiously, there is a lack of lacustrine fauna (fresh and saline water-tolerant) within the beach ridge grainstone and equivalent sediments in the basin. Possible explanations for this are: 1) post-depositional dissolution of organisms caused by a change in the physical and chemical environments; 2) destruction of shells during high energy transport rendering them unrecognisable in the sediment record; and 3) the high-energy, sandy lake basin may have been unsuitable for lacustrine organisms.

Formation of the ridge may have commenced considerably earlier than 320 ka, which marks the waning stages of deposition from the lee side of the ridge. Wilson (1991)[1] proposed that the emplacement of the Bridgewater Formation dunes along the west coast of the Eyre Peninsula occurred during sea-level highstands as early as 700 ka (onset of Oxygen Isotope Stage 17). Therefore, it is likely that ridge accretion also occurred episodically throughout Oxygen Isotope Stages 17 to 7 and Stage 5 interglacials (Fig. 8), until the sediment supply was exhausted and recharge rates decreased due to a fall in eustatic sea-level, giving rise to a new depositional regime in the Lake Malata-Lake Greenly Complex. A comprehensively dated sequence through the Lake Malata ridge could potentially provide palaeoclimatic information prior to 320 ka.

Palaeoclimate ca. 320-115 ka

We have no direct record of sedimentation and evolution of the lake system for the period 320-115 ka. As mentioned earlier, the Lake Malata ridge may have continued accreting intermittently during pluvial episodes, particularly during Oxygen Isotope Stage 7 until ~ 180 ka, when the emplacement of Phase II dunes along the west coast of the Eyre Peninsula was most intense (Wilson 1991)[1]. The morphology and pedogenic alteration of subparabolic dunes overlying thick carbonate sequences south of Lake Greenly (Dutkiewicz 1996)[2] are consistent with a later episode of Wilson's (1991)[1] Phase II dune emplacement during the last interglacial (Stage 5; Fig. 8). This suggests that deposition of lacustrine carbonates most likely occurred prior to and intermittently during the warm interstadials of Oxygen Isotope Stage 6 and during the warm intervals of the last interglacial (Oxygen Isotope Sub-stage 5e). Landward migrating subparabolic dunes would have buried regions relatively close to the coast, whereas more distal areas, such as Lake Malata, would have been subject to continued carbonate precipitation. Large volumes of this mud are likely to have been deflated into lunettes during Oxygen Isotope Stage 6, which is broadly similar to stages 4, 3 and 2 during which lunette deposition was pervasive. Further sampling and dating is required to decipher the palaeoclimate record during this period.

Multiple Arid Episodes ca. 115-16 ka

Lunettes form by deflation of sand-sized material, which commonly includes pelletised clays derived from a drying lake floor by uni-directional wind (Bowler 1973; 1980; 1983). Factors involved in the construction of clay pellet lunettes (fluctuating groundwater levels, uni-directional wind, aridity) have been discussed extensively by Bowler (1973) and the same explanation can be applied to the carbonate pellet lunettes from the Lake Malata-Lake Greenly Complex. The ages of the lunettes indicate that seasonally arid climates and intense prevailing westerly winds in southern Australia occurred several times since the last interglacial. Although the TL ages are not sufficiently precise to date the exact onset of each arid episode, at the very least they indicate the time when lunette building was in full swing. In general, these correlate with periods of relatively low eustatic sea-level and oscillations to cold intervals, many of which had not previously been associated with continental aridity and lunette building. The oldest lunette horizon dated *ca.* 115 ka corresponds to the last glacial inception and termination of the last interglacial (Oxygen Isotope Sub-stage 5d). Aeolian activity increased again at *ca.* 96 ka (Oxygen Isotope Sub-stage 5c), 85 ka (cold Sub-stage 5b), and 75 ka and 70 ka (Sub-stages 5a/4). Significantly, a strongly-indurated pedogenic horizon dated at *ca.* 75 ka suggests that the lunette material was most likely modified soon after the shift from stage 5 to 4 which globally marks the main glacial transition. Similar periods of deflation and pedogenesis are estimated to have occurred around 90 ka and before about 70 ka in the Madigan Gulf at Lake Eyre (Magee *et al.* 1995). Lunette-building in the Lake Malata-Lake Greenly complex occurred twice during the interstadial of stage 3 with maximum aeolian activity centred around the two cold stadials ca. 54 ka and 43 ka immediately following the end of the main glacial transition. These ages likely correspond to the 60-50 ka playa deflation phase and dune building at Lake Eyre (Magee & Miller 1998). Unlike Lake Eyre, however, there is no evidence at Lake Malata or Lake Greenly for a major lacustral phase in the period 50-35 ka (Magee & Miller 1998). However, further excavation work is required to test whether a beach deposit of this age might be buried beneath younger aeolian sediments.

Several lunettes in the lake system dated at *ca.* 18 ka, 17 ka and 16 ka, cluster on Oxygen Isotope Stage 2, which marks the peak of the last glaciation for the Australian continent around 20 and 17 ka (e.g., Bowler 1986; Colhoun 1991). The age of the oldest lunette near this cluster dated at ca. 26 ka corresponds to the transition between Oxygen Isotope Stage 3 and Stage 2, indicating that the onset of arid conditions and lunette-building during the last glacial maximum commenced as early as 26 ka in this part of Australia. This corresponds to a general decrease in the number of high and intermediate lakes in Australia after 26 ka (Harrison 1993) and the onset of a dry-lake phase around 30 ka at Lake Eyre (Magee & Miller 1998). Aeolian activity appears to have peaked ca. 17.5-16 ka, which correlates well with the Last Glacial Maximum at 17.9 ka (Martinson *et al.* 1987). During this glacial period the sea level was at its lowest and the climate experienced intensified aridity and high westerly wind speeds (Bowler & Wasson 1984; Petit *et al.* 1990) conducive to pervasive dune-building over arid and semi-arid regions of Australia (Bowler & Wasson 1984; Wasson 1986). Lunette-building was in its waning stages ca. 16-15 ka, with local deposition still occurring locally until ca. 15.6 ka and was restricted to northern parts of the lake complex. Based on records from approximately 35 Australian lakes Harrison and Dodson (1993) suggest a brief interval to wetter conditions during 15-13 ka, which is consistent with absence of lunette sequences at Lake Malata. These authors further propose that arid conditions persisted after the last glacial maximum culminating in maximum aridity at 12 ka, by which time most Australian lakes were dry. This would correspond to pedogenesis of Last Glacial Maximum lunettes in the lake complex.

Wet-arid cycles in the Holocene

Gypsum lunettes in the Lake Malata-Lake Greenly Complex have formed in two stages, in a slightly different manner to carbonate pellet lunettes. The gypsum first precipitated within the lake basin in association with groundwater oscillations and evaporation at the capillary fringe (Teller *et al.* 1982; Bowler & Teller 1986; Magee 1991). Although sand-sized discoids exposed during a dry period when the lake levels are low are easily deflated by prevailing winds, the similarity in grain-size and morphology of gypsum forming present-day beaches and the youngest lunettes at Lake Malata suggests that the most recent gypsum lunettes most likely formed by deflation of reworked material deposited at the lake margin during an earlier relatively higher lake level. Since surficial sediments in the Lake Malata basin are dominated by hemi-pyramidal gypsarenite, a combination of a thin skin of water and strong wind would provide an efficient mechanism for transporting and depositing the gypsum at the lake margin. Transportation by wave action is further supported by the presence of ripple marks on gypsarenite-dominated playa surfaces and by the abundance of biogenic fragments within the most recent deposits. The gypsum is subsequently deflated and sorted during a more arid period. Therefore, the gypsum lunettes most likely represent foredunes deposited under seasonally oscillating relatively high lake levels and relatively low lake levels in response to changing evaporation/inflow. Strong winds dominated by a westerly component are required throughout the entire cycle of deposition and reworking. A single AMS-dated horizon from the middle of the lunette indicates that this process was well underway ca. 5.6 ka cal B.P. most likely coinciding with the Holocene sea-level highstand *ca.* 6.4 ka (Belperio *et al.* 2002). The mean annual precipitation at this time is estimated to have increased by 20-50% (Wasson & Donnelly 1991) with maximum lake levels recorded at most sites in Australia (Bowler 1981; Wasson & Donnelly 1991; Harrison 1993; Harrison & Dodson 1993).

Although gypsum lunettes have formed in the relatively recent past at Lake Malata, this has not been the case at Lake Greenly. The reason for this is that at Lake Greenly gypsum occurs several decimetres below the lake surface beneath dolomitic carbonate muds (Dutkiewicz & von der Borch 1995). In this scenario, surficial carbonate would first have to be pelletised and deflated before interstitial gypsarenites are exposed to undergo reworking. Therefore, while gypsum lunettes were forming in the relatively recent past at Lake Malata, carbonate ridges were more likely to form concurrently at Lake Greenly. The complex system of lunettes and ridges at the eastern margin of Lake Greenly suggests that this may have been the case. The fragmented nature of the ostracode valves in the Lake Greenly ridges serves as an indication of reworking by wave action during relatively higher lake levels. The ridges constitute a prograding sequence formed by exposure of lacustrine carbonate mud under gradually regressing lake shorelines. The carbonate mud has undergone subsequent stabilisation by vegetation followed by pedogenesis and induration in the subaerial vadose environment. Consequently, these beach ridges are excellent indicators of the former lake extent and although undated may be concurrent with the formation of gypsum lunettes at Lake Malata.

The recent 3 m-high beach deposit (ML18, Fig. 2) at Lake Malata the remobilisation of which has been dated at ca. 1 – 1.93 ka (Dutkiewicz & Prescott 1997), represents a foredune formed by aeolian reworking of coarse beach sand. Aeolian deposition is supported by the finer grain-size and better sorting of the sand compared to other beach deposits of broadly similar composition, and by the presence of carbonate peloids. In particular, the coquina layer within the deposit is indicative of a lacustral period during which relatively high lake levels and lower salinities caused by increased precipitation and/or decreased evaporation rates would have allowed large numbers of *Coxiella* gastropods to inhabit Lake Malata. The orientation of the foredune along the south-eastern shoreline is consistent with the orientation of prevailing south-westerly winds, which operate during the dry summer months. Aeolian activity was generally high at this time and is further supported by the most recent lunette-building episode in the Lake Malata region dated at ca. 1.2 ka (Dutkiewicz & Prescott 1997).

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